

Process Study of Oceanic Responses to Typhoons Using Arrays of EM-APEX Floats and Moorings

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LONG-TERM GOALS

Our long-term scientific goals are to understand the upper ocean dynamics, to understand the coupling between the ocean and atmosphere via air–sea fluxes, and to quantify the mechanisms of air–sea interactions. Our ultimate goal is to help develop improved parameterizations of air–sea fluxes in ocean–atmosphere models and parameterizations of small-scale processes in the upper ocean and the stratified interior.

OBJECTIVES

Tropical cyclones derive energy from the ocean via air–sea fluxes. Oceanic heat content in the mixed layer and the air–sea enthalpy flux play important roles in determining the storm’s maximum potential intensity, structure, energy, trajectory, and dynamic evolution. The most energetic oceanic responses to tropical cyclone forcing are surface waves, wind-driven currents, shear and turbulence, and inertial currents. Quantifying the effect of these oceanic processes on air–sea fluxes during tropical cyclone passage will aid understanding of storm dynamics and structure. The ocean’s recovery after tropical cyclone passage depends upon small- and meso-scale oceanic processes in the storm’s wake region. These processes are the least understood primarily because of the paucity of direct field observations under passing tropical cyclones; as a consequence, there are large uncertainties in air–sea flux parameterizations in extreme wind regimes.

We designed an experiment to make in-situ oceanic observations in the western Pacific Ocean on the paths of tropical cyclones to understand the coupled atmospheric–oceanic dynamics in a wide range of conditions. Our broad focus is on surface waves, inertial waves, shear instability, internal waves, and

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meso-scale eddies before, during, and after the passage of tropical cyclones. Primary objectives of this project are (1) to provide observations of oceanic responses to a wide range of atmospheric wind forcings including tropical cyclones, (2) to provide observations of the effect of various oceanic conditions on the strength of tropical cyclones, and (3) to help provide better parameterization schemes for air–sea fluxes, especially in the tropical cyclone extreme wind forcing regime and for interior ocean mixing.

APPROACH

Long-term observations of atmospheric forcing and upper oceanic conditions were made by moorings in the western Pacific Ocean, in collaboration with Taiwanese colleagues, on the popular paths of tropical cyclones in 2009 and 2010. During the 2010 typhoon season (the intensive observation period of ITOP), subsurface temperature measurements on the moorings were transmitted via Iridium satellite, and one upward-looking 75-kHz Long Ranger ADCP was deployed on each of three subsurface moorings. Two arrays of seven EM-APEX floats each were air-launched in front of typhoons Fanapi and Megi; the floats transmitted near-real time observations of velocity, temperature, salinity, and GPS position via Iridium satellite.

WORK COMPLETED

Four ATLAS surface moorings (A1, A2, A3, and A4) and three subsurface moorings (SA1, SA2, and SA4) were deployed in the western Pacific Ocean before summer 2010. In November 2010 two of four surface moorings and all three subsurface moorings were recovered. Two surface buoys (A1 and A3) were broken off from the moorings by Typhoon Megi. All underwater instruments and data were lost.

Seven EM-APEX floats were launched from C130 aircraft on 17 September 2010, one day ahead of Typhoon Fanapi. Based on the forecast, three floats were launched to the right of the eye of Fanapi, one on the eye, and three to the left, with 25 n mi separation between floats. The forecast of the typhoon track was very accurate and the eye of Fanapi passed the center of the float array as planned. After the deployment, these floats profiled vertically between the surface and 250-m depth taking measurements of temperature, salinity, pressure, and horizontal velocity. When at the surface, they transmitted GPS positions, temperature, salinity, pressure, and horizontal velocity data via Iridium satellite communications. Unfortunately, strong surface waves forced by the tropical cyclone may have damaged the floats' ballasting system, causing problematic connections between the floats and Iridium satellites. The transmission of GPS fixes was intermittent throughout the mission; the transmission of temperature, salinity, pressure, and horizontal velocity data was mostly successful until all floats suddenly stopped transmissions about 10 days after their deployment.

Another array of seven EM-APEX floats was launched on 16 October 2010, one day ahead of Typhoon Megi. The plan for float placement was similar to that for Typhoon Fanapi, three to the right of eye, one at the eye, and three to the left of eye based on the forecast, with 20 n mi separation between adjacent floats. Unexpectedly, the eye of Megi passed over the southern-most float of the array; therefore six floats sampled the ocean to the right of Typhoon Megi and one at the eye. The floats made vertical profiles between the surface and 250-m depth before and after the passage of Megi. During storm passage, floats profile between 30 and 250-m depths, staying at least 30 m below the sea surface to avoid possible damage to their ballasting systems, a lesson learned from the Typhoon Fanapi mission. All seven floats were recovered successfully 3–4 days after their deployment.

RESULTS

Typhoon Fanapi observed by EM-APEX floats (Rosalinda Mrvaljivitch and Andy Hsu)

Several tens of thousands of temperature profiles are used to investigate the thermal evolution of the cold wake of Typhoon Fanapi, 2010. Typhoon Fanapi (Fig. 1) formed a cold wake in the Philippine Sea on 18 September characterized by a mixed layer that was $>2.5^{\circ}\text{C}$ cooler than surrounding water, and extending to >80 m, twice as deep as the pre-existing mixed layer. The initial cold wake became capped after 4 days as a warm, thin surface layer formed (Fig. 2). The thickness of the capped wake, defined as the 26°C to 27°C layer, decreased, approaching the background thickness of this layer with an e-folding time of 23 days, almost twice the e-folding lifetime of the Sea Surface Temperature (SST) cold wake (12 days). The wake was advected hundreds of kilometers from the storm track by a pre-existing mesoscale eddy. Its thermal structure could not be reproduced with a 2-layer model based on remote sensing measurements of SST and sea level anomaly, and climatology. The observations reveal new intricacies of cold wake evolution and demonstrate the challenges of describing the thermal structure of the upper ocean using sea surface information alone. (Fig. 3)

We focus on a study of the near-inertial and subinertial waves induced by Typhoon Fanapi. The EM-APEX float 4913a was located near the maximum inertial resonant region; the float's velocity field is decomposed into tidal, inertial, and subinertial motions. The decomposition is calculated on the isopycnal coordinate to prevent the artificial results from the initial pumping. The zonal velocity at subinertial frequency shows that a subsurface subinertial jet is fully developed one day after the Typhoon Fanapi pass (Fig. 4, top panel). The subinertial jet may play an important role in trapping the near-inertial waves. Near-inertial energy propagates downward initially right after Typhoon Fanapi but remains in the thermocline for about 3 days, instead of penetrating deeper (Fig. 4, lower panel). There are two possible explanations for the persistent near-inertial wave in the thermocline. First, the positive geostrophic vorticity associated with the subinertial jet induced by Typhoon Fanapi stopped the near-inertial wave. It had lower intrinsic frequency, which cannot propagate freely [Kunze, 1985]. Second, the slowly propagating high-mode, near-initial waves are left behind after the fast propagating, low-mode waves leave the site [Gill, 1983].

The pre-Fanapi vorticity field from the Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO) data shows there were several background eddies, two cyclonic eddies, and one anticyclonic eddy (Fig. 5, top left panel). The vertical structure of the background vorticity from the array of EM-APEX floats shows similar pattern as AVISO with strong negative vorticity $-0.2 - -0.4 f_0$ at the subsurface (Fig. 5, top right panel). The subinertial jet induced by Typhoon Fanapi shows positive vorticity $0.3 f_0$ at the eye of Fanapi and negative vorticity ($-0.1 f_0$) at the background (Fig. 5 bottom panel). Because of the asymmetric wind field, the positive vorticity extends to the right of the Fanapi track with depth. The equatorward near-inertial waves may be reflected due to positive vorticity and the poleward near-inertial waves may be trapped due to inertial frequency increases with latitude [Garrett, 2001].

The PWP3D model was used to simulate the ocean thermal response in Sanford et al. [2011]. Their model results agreed with the EM-APEX float data by showing temperature decreasing 2.5°C in the mixed layer during Hurricane Frances. A similar simulation was made for Typhoon Fanapi. Our simulation shows there is 1.5°C unpredicted cooling during Fanapi (Fig. 6). There are several possible causes such as inaccurate initial conditions, missing surface heat and buoyancy flux in the model, float advection, and background eddy and evolution. We will investigate the discrepancy further.

Typhoon Megi drag from EM-APEX floats (student Andy Hsu)

The momentum budget method of Sanford et al. [2011] is used to calculate the drag coefficient. The equation

$$\int_{-H}^0 \mathbf{u}_t + f\mathbf{k} \times \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u} + \mathbf{u} \nabla \cdot \mathbf{u} \approx \frac{\boldsymbol{\tau}_w}{\rho_0} + \frac{\nabla \cdot \mathbf{p}}{\rho_0}$$

is evaluated using a PWP3D model to determine how well the first 2 terms, which can be easily measured using EM-APEX floats, can estimate the drag. \mathbf{u}_t is the time derivative of velocity; $f\mathbf{k} \times \mathbf{u}$ is the Coriolis acceleration; $\mathbf{u} \cdot \nabla \mathbf{u}$ is the advection term; $\mathbf{u} \nabla \cdot \mathbf{u}$ is the divergence term; $\boldsymbol{\tau}_w$ is the surface wind stress; and $\frac{\nabla \cdot \mathbf{p}}{\rho_0}$ is the pressure gradient term. The integration depth is from the surface to

150 m. The model is driven using a storm wind model and a drag coefficient from Powell [2003]. We test whether the drag computed via momentum budget is the same as that input to the model. There is no other external forcing inside the model except for hurricane wind. Fig. 7 shows the results at a data point 32 km on the left side of the track. Most of the surface stress comes from the linear term:

$\mathbf{u}_t + f\mathbf{k} \times \mathbf{u}$, before the hurricane passed. The pressure gradient term is not important until the hurricane passed. The advection and divergence terms are relatively small compared with others. We compare actual wind stress in the model and the wind stress derived via momentum budget in Fig. 7 (f). The difference is very small. The bulk formula is $\boldsymbol{\tau}_w = C_d U_{10} |\mathbf{U}_{10}|$. C_d is the drag coefficient, and U_{10} is wind speed at 10 m. If we calculate the drag coefficient by only linear terms, it does not differ from the actual wind stress before the hurricane passed, as in Fig. 7 (i). This gives us confidence that the EM-APEX data can be used to estimate drag, at least for the first part of the storm.

IMPACT/APPLICATION

Tropical cyclones cause strong oceanic responses, e.g., surface waves, inertial waves, and a deepening of the surface mixed layer. To improve the modeling skill of oceanic responses to tropical cyclones and the prediction of tropical cyclones, we need to understand the small-scale processes responsible for the air-sea fluxes and interior oceanic mixing, and the meso-scale oceanic processes that modulate the background oceanic heat content. The present field experiment will provide direct observations of oceanic responses forced by tropical cyclones and the ocean's recovery, as well as aid understanding of the dynamics of small- and meso-scale oceanic processes. These observations will help improve the prediction skill of oceanic and atmospheric models in high wind regimes.

RELATED PROJECTS

Energy Budget of Nonlinear Internal Waves Near Dongsha (N00014-05-1-0284) as a part of NLIWI DRI: In this project, we study the dynamics and quantify the energy budget of nonlinear internal waves (NLIWs) in the South China Sea using observations taken from two intensive shipboard experiments in 2005 and 2007 and a set of nearly one-year velocity-profile measurements taken in 2006–2007 from four bottom mounted ADCPs across the continental slope east of Dongsha Plateau in the South China Sea. Results of NLIWI DRI will help improve our understanding of the dynamics of internal waves and their effects on the turbulence mixing in the upper ocean.

Study of Kuroshio Intrusion and Transport Using Moorings, HPIES, and EM-APEX Floats (N00014-08-1-0558) as a part of QPE DRI: The primary objectives of this observational program are 1) to quantify and to understand the dynamics of the Kuroshio intrusion and its migration into the southern East China Sea (SECS), 2) to identify the generation mechanisms of the Cold Dome often found on the SECS, 3) to quantify the internal tidal energy flux and budgets on the SECS and study the effects of the Kuroshio front on the internal tidal energy flux, 4) to quantify NLIWs and provide statistical properties of NLIWs on the SECS, and 5) to provide our results to acoustic investigators to assess the uncertainty of acoustic predictions. Results of this DRI program will help understand oceanic physical processes on the southern East China Sea, e.g., the cold dome. Typhoons may modulate the Kuroshio, the Kuroshio intrusion, and other oceanic processes that result in cold pools on the continental shelf of the southern East China Sea.

PUBLICATIONS (wholly or in part supported by this grant)

- D'Asaro, E., P. Black, L. Centurioni, P. Harr, S. Jayne, I.-I. Lin, C. Lee, J. Morzel, R. Mrvaljevic, P.P. Niiler, L. Rainville, T. Sanford, and T.Y. Tang. 2011. Typhoon-ocean interaction in the western North Pacific: Part 1. *Oceanography*, **24**(4):24–31, <http://dx.doi.org/10.5670/oceanog.2011.91>. [refereed]
- Mrvaljevic R.K., P.G. Black, L.R. Centurioni, Y.-T. Chang, E.A. D'Asaro, S.R. Jayne, C.M. Lee, R.-C. Lien, I.-I. Lin, J. Morzel, P.P. Niiler (deceased), L. Rainville, and T... Sanford. 2012. Observations of the cold wake of Typhoon Fanapi. *Geophys. Res. Lettr.* [submitted, referred]
- Pun, I.F., Y.-T. Chang, I.-I. Lin, T.Y. Tang, and R.-C. Lien. 2011. Typhoon-ocean interaction in the western North Pacific: Part 2. *Oceanography*, **24**(4):32–41, <http://dx.doi.org/10.5670/oceanog.2011.92>. [refereed]
- Sanford, T.B., J.F. Price, and J.B. Girton. 2011. Upper-ocean response to Hurricane Frances (2004) observed by profiling EM-APEX Floats. *J. Phys. Oceanogr.*, **41**, 1041–1056, doi: <http://dx.doi.org/10.1175/2010JPO4313.1>. [refereed]

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None

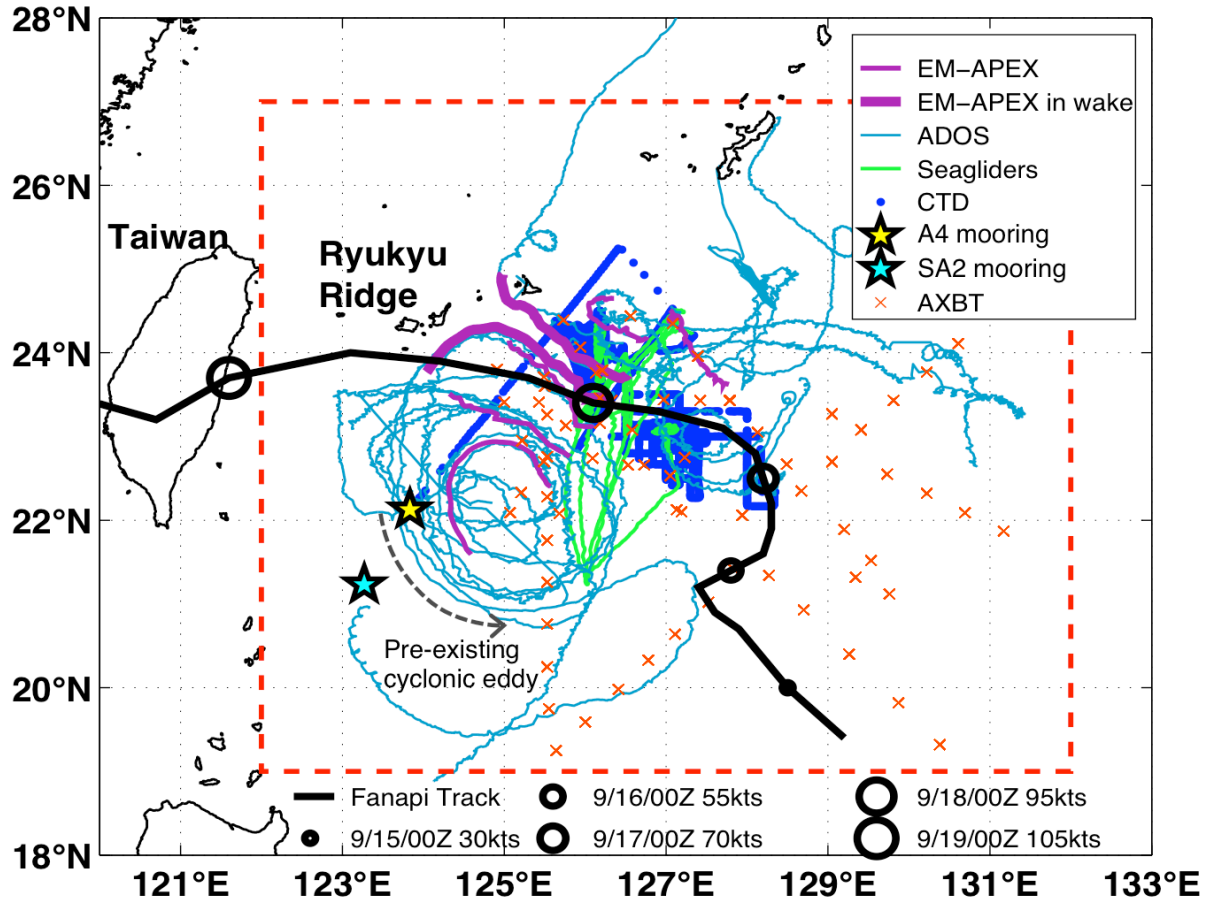


Figure 1. Chart of all assets used in this study with the best track of Typhoon Fanapi. Typhoon Fanapi passed over the Philippine Sea during 15–19 September, executing an S-shaped track as the intensity increased. Tens of thousands of temperature profiles were obtained from 7 EM-APEX floats, 19 ADOS drifters, 9 Seagliders, 3 weeks of UCTD, two moorings, and 72 AXBTs. Float and drifter tracks identified a large cyclonic eddy south of the storm track. The red dotted rectangle is the Typhoon Fanapi region discussed in the text.

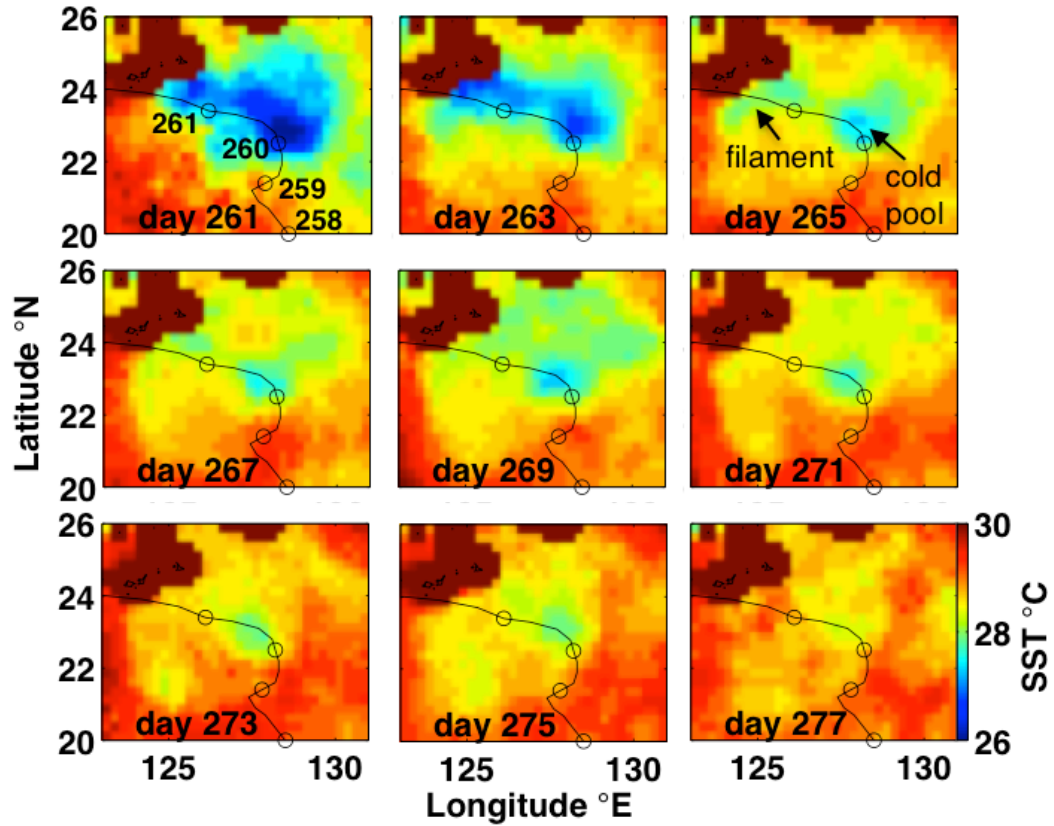


Figure 2. The SST cold wake of Typhoon Fanapi from the Remote Sensing Systems (RSS) microwave-only optimal interpolation (MW OI) SST product. Every other day is shown, starting the day after Fanapi passed over the EM-APEX and ADOS deployment line. The SST wake warmed rapidly in the first few days, and then more slowly over the following weeks. The eastern cold pool remained a persistent cool feature, while the SST shows evidence of the filament part of the wake being advected around the pre-existing cyclonic eddy found south of the storm track.

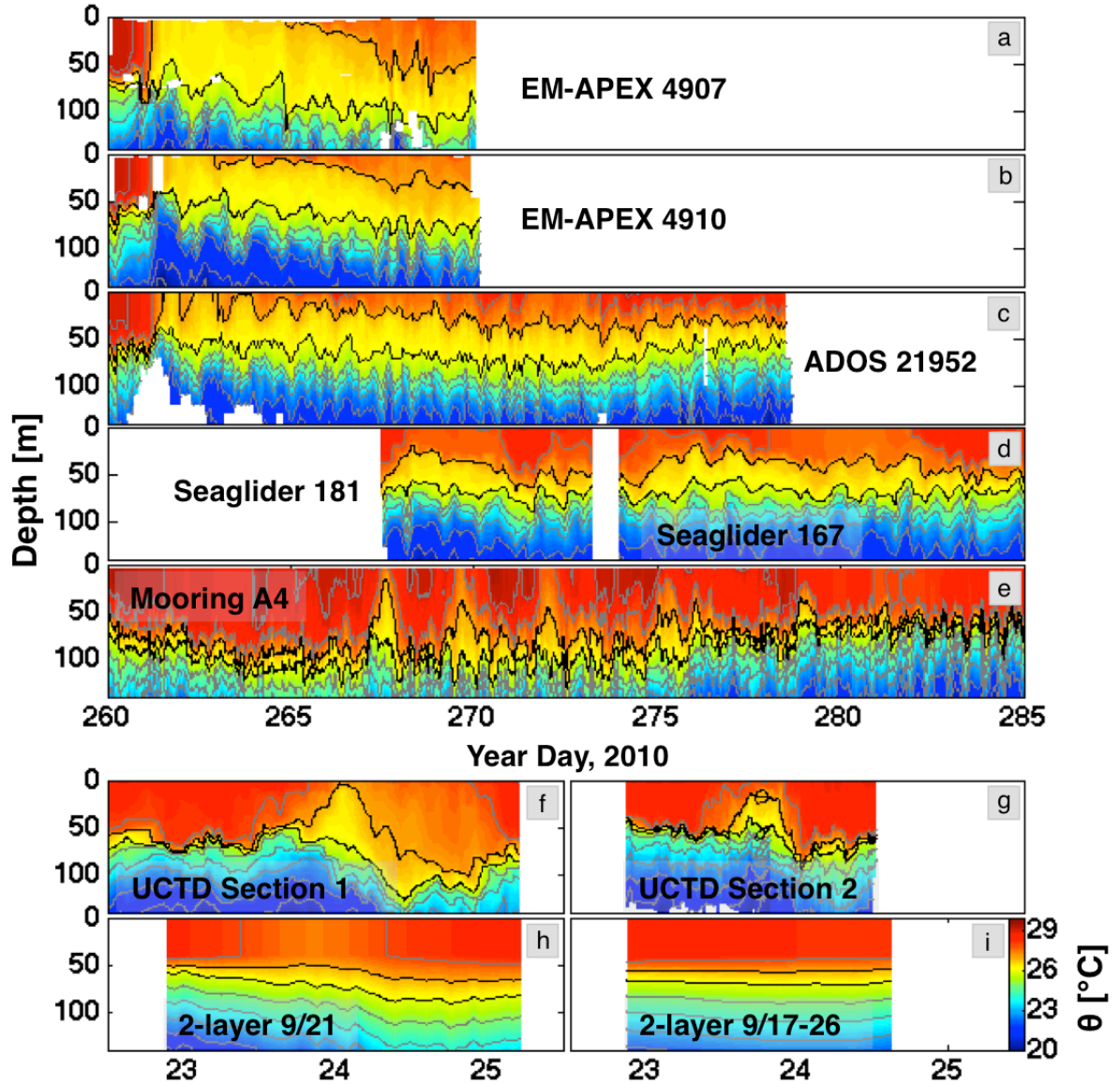


Figure 3. Potential temperature time series between 17 September and 12 October with contours every 1°C from selected floats and drifters (a–c), Seagliders (d), a mooring (e), wake cross sections from the ship-board UCTD around year day 265 (f) and 266 (g), a 2-layer model (TLM; [Lin et al., 2008; Shay et al., 2000]) estimate of the cross section using a single altimeter pass on 09/21 (h), and a TLM estimate using a 10-day map of SSHA from 09/17 to 09/27 (i). The difference in depth between the 26°C and 27°C isotherms (highlighted contours) is the thickness of the cold wake. The vertical motions of the isotherms in a–c are primarily a combination of inertial pumping (period ~30 hours) and internal tides, which are strong in this region. The TLM, which uses remote sensed SST and SSH to estimate the thermal structure of the water column, fails to display the subsurface cold wake signature, even when a single altimeter pass directly over the cold wake is used in the model (h).

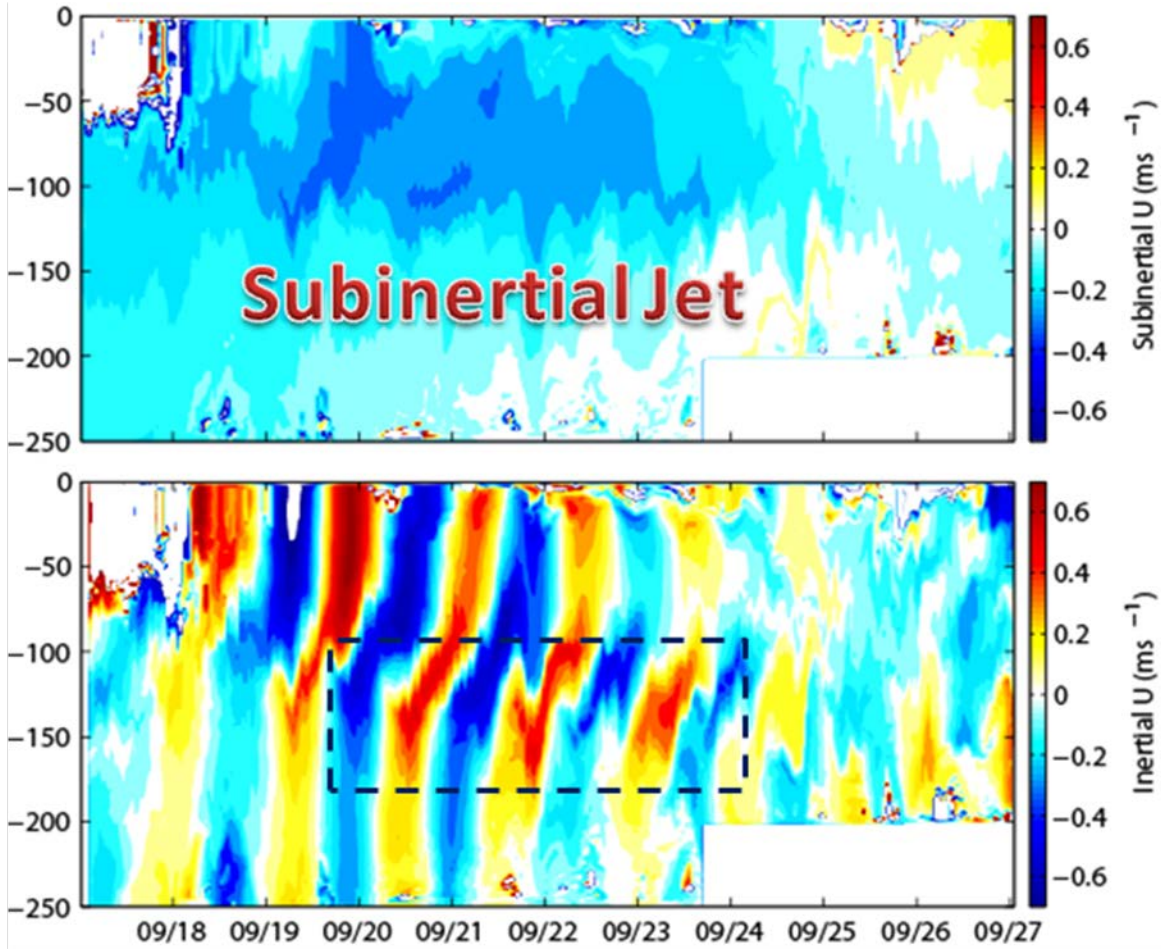


Figure 4. The zonal velocity contours at subinertial (top panel) and inertial frequencies (bottom panel) from EM-APEX 4913a. The decomposition into the tide, inertial current, and subinertial current, is calculated on the isopycnal coordinate. A strong subinertial jet develops one day after the Fanapi pass (upper panel). Near-inertial energy propagates downward initially, but remains in the thermocline ~3 days after the Fanapi pass (lower panel). The location of EM-APEX 4913a is shown in Fig. 5, top-left panel (blue circle).

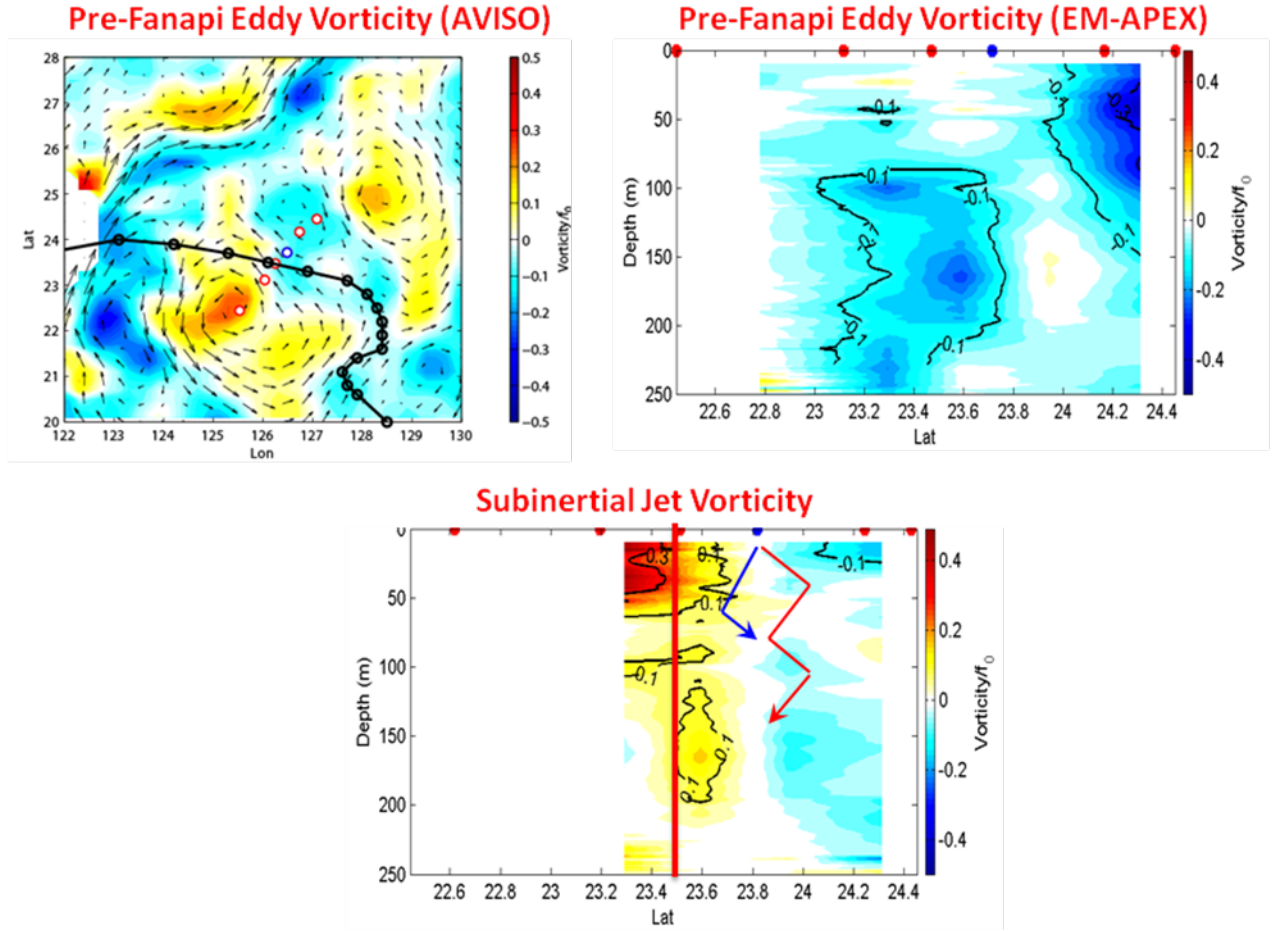


Figure 5. Top-left panel is the pre-Fanapi surface vorticity field from AVISO (the black circles indicate the best track of Typhoon Fanapi, the blue circle indicates the location of EM-APEX 4913a, the red circles indicate the locations of other EM-APEX floats). Top-right panel is the vertical structure of the vorticity field from the array of EM-APEX floats (the float locations are marked on the top). Bottom panel is the subinertial jet vorticity from EM-APEX float observations. The thick red line indicates the center of the Typhoon Fanapi, the thin blue and red lines indicate the possible mechanisms of reflecting and trapping of the equatorward and poleward near-inertial waves.

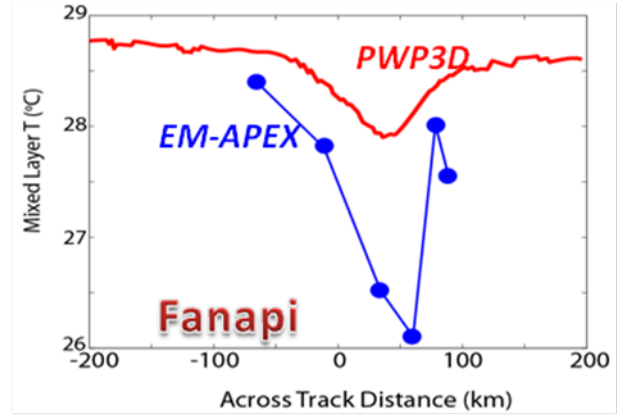
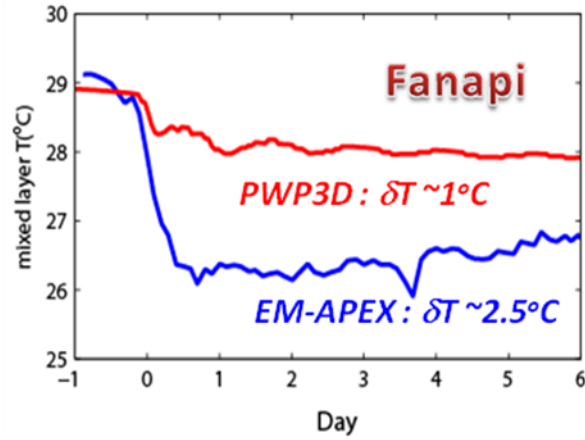


Figure 6. Left panel is the evolution of the mixed layer temperature from the EM-APEX float (blue curve) and the prediction of PWP3D model (red curve) during Typhoon Fanapi. Right panel is the spatial variation of the mixed layer temperature across the track of Typhoon Fanapi after 1.7 days.

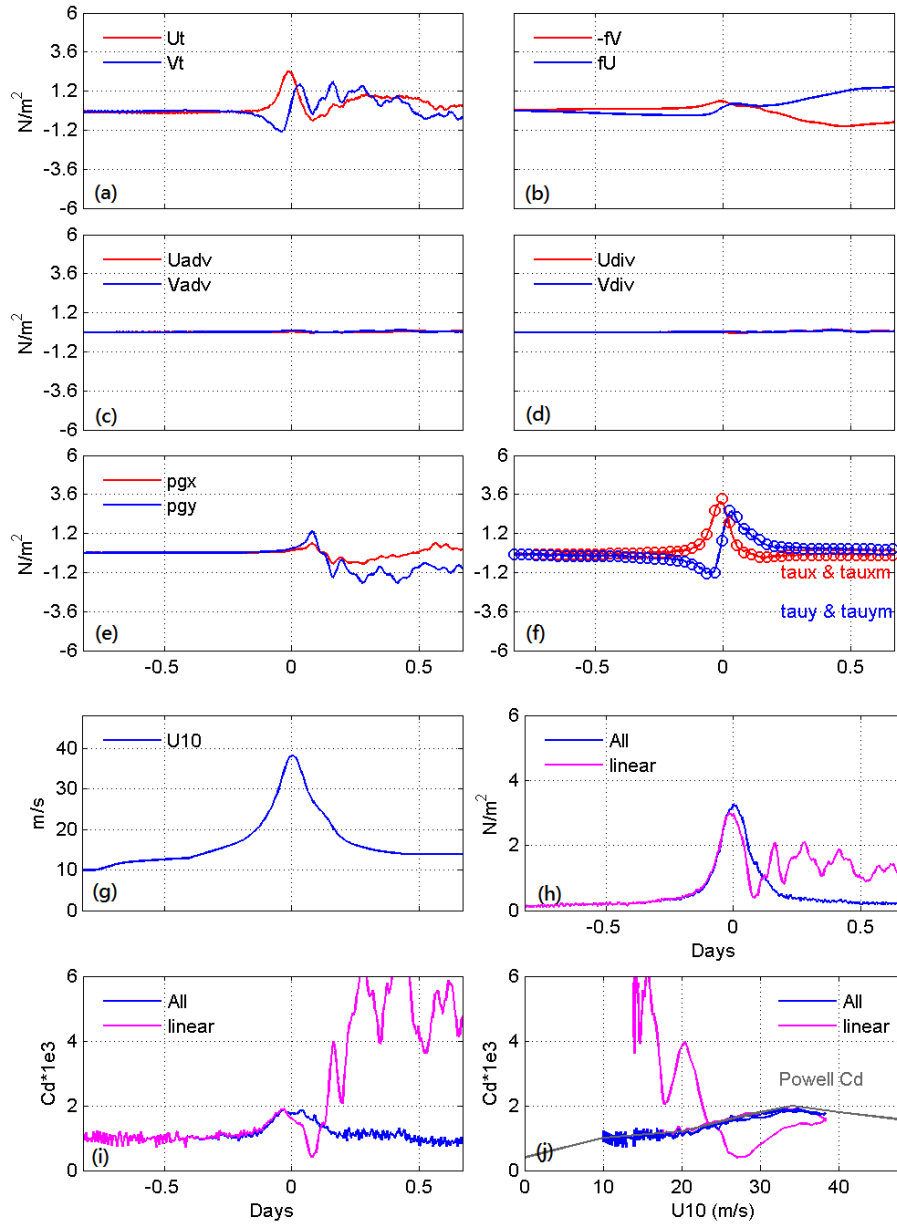


Fig. 7 The data point in PWP3D at 32 km on the left of Typhoon Megi track. (a) The time derivatives of velocity; (b) the Coriolis acceleration; (c) the advection term; (d) the divergence term; (e) the pressure gradient term; (f) the solid line is the wind stress derived from momentum budget (the sum of (a)~(e)), and the circle is the actual wind stress in the model; (g) U_{10} ; (h) the blue line is the wind stress calculated from all the terms, and the pink line is only from linear term; (i) the change of C_d with time. The blue line is C_d from all the terms, and the pink line is from linear terms; (j) Rewrite (i) as the function of U_{10} . The black line is the Powell's function in 2003.

REFERENCES

- Garrett, C. 2001. What is the “near-inertial” band and why is it different from the rest of the internal wave spectrum?, *J. Phys. Oceanogr.*, **31**(4), 962–971.
- Gill, A. 1983. *Atmosphere-Ocean Dynamics*, Academic Press, 662 pp.
- Kunze, E. 1985. Near-inertial wave propagation in geostrophic shear, *J. Phys. Oceanogr.*, **15**(5), 544–565.
- Lin, I.-I., C.-C. Wu, I.-F. Pun, and D.-S. Ko. 2008. Upper-ocean thermal structure and the western North Pacific category 5 typhoons. Part I: Ocean features and the category 5 typhoons’ intensification, *Mon. Wea. Rev.*, *136*, 3288–3306, doi:10.1175/2008MWR2277.1
- Powell, M.D., P.J. Vickery, and T.A. Reinhold. 2003. Reduced drag coefficient for high wind speeds in tropical cyclones. *Nature*, **422**, 279–283.
- Sanford, T.B., J.F. Price, and J.B. Girton. 2011. Upper-ocean response to Hurricane Frances (2004) observed by profiling EM-APEX Floats. *J. Phys. Oceanogr.*, **41**, 1041–1056, doi: <http://dx.doi.org/10.1175/2010JPO4313.1> .
- Shay, L. K., G. J. Goni, P. G. Black. 2000. Effects of a warm oceanic feature on Hurricane Opal, *Mon. Wea. Rev.*, *128*, 1366–1383, doi:10.1175/1520-0493(2000)128<1366:EOAWOF>2.0.CO;2